First look at the proton imaging project

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Outline

- History of proton imaging
- Pros and cons of proton imaging
- X-ray radiography vs proton radiography
- Modeling proton imaging: GEANT4?
- Scintillator detectors

History of proton imaging

- The first proton radiography of human tissues was done by A. M. Koehler in 1973:
  - A passive photographic plate behind the sample recorded projected images of an incident beam, according to the transmission efficiency of the protons
  - The proton beam energy had to be tuned to center the Bragg peak on the photographic plate in order to get useful density contrast
  - Sharp features blurred by the phenomenon of multiple Coulomb scattering (MCS), resulting in a resolution of around 3 to 5 mm
- Later studies (K. Hanson et. al (1981), U. Schneider et. al (1994)) showed that the spatial resolution of proton radiography and CT can be improved to about 1-2 mm by tracking individual protons in coincidence as they enter and exit the imaged objects

Pros and cons of proton CT

- Pros: very high contrast, i.e. very good density resolution
  - As the density resolution is inversely proportional to the square of the slope of the transmission curve, the density resolution per transmitted proton is many thousands of times better using protons than using X-rays because of the much larger energy deposition of protons. In practice protons demonstrate about 5x higher density resolution than X-rays through a 25-cm water equivalent for the SAME DOSE deposited. This higher resolution realizes more detailed tomography and detection of density anomalies in soft tissue than is possible with X rays.
  - Can be used to verify the correct delivery of a proton treatment plan while the patient is in the treatment position
  - Proton dose calculations have been performed using X-ray CT. But the accuracy of xCT for proton treatment planning is limited due to the difference in physical interactions between photons and protons, i.e. have different density maps
- Cons: poor spatial resolution
  - The proton beam will spread out through the process of multiple Coulomb scattering (MCS). For example, a 200 MeV beam will acquire an rms transverse size of 6.5 mm by the end of its range in water

X-ray radiography

- In an X-ray radiograph, variations in the internal structure of the specimen lead to intensity variations in the transmitted X-rays and in the darkness of the photographic image
  - X-rays are absorbed or scattered and therefore have a characteristic exponential dependence on the path length through the object
  - Current high resolution PET/CT scans have resolutions of ~0.3 - 0.4 mm

Proton radiography

- Need to know the incident angle and the energy of the individual protons at good accuracy
- Challenges to be addressed:
  - The large angular distribution of the particles must be accommodated
  - The scattering envelope of the particles must be modeled
  - The massive amount of projection data must be managed efficiently
  - The reconstruction must be accomplished within a reasonable amount of time, i.e. on the order of minutes

Modeling proton imaging: G4?

- From Hide Tanaka:
  - Did not modify parameters in G4 simulation
  - Used package "QGSP-Bertini" for energy region ~300 MeV - 5 GeV
  - No energy resolution of proton tracks available
- From Lindley Winslow:
  - Con: beware of low energy nuclear physics (20 MeV and below).
    - Suggestion: look at forums to see what people are saying and there should be some talks from recent tutorials that give you the current performance of G4 compared to various experiments for protons
  - Pro: G4 is trivial for changing energy, angle and particle type. It uses physics lists to modify the physics that goes into the model
    - Need to code up the media and shapes
- From Tom Roberts:
  - G4 is the "best available software out there" to model a proton beam"
  - Will need to write additional code to model a detector and handle output data

G4 continued

- Have downloaded G4 beamline from Muon's Inc. website
- Will start producing simple simulations for next week

G4 used in proton tomography

- A number of research projects have involved running G4 Monte Carlo simulations for proton tomography:
- H. Sadrozinski et. al, "Toward proton computed tomography." IEEE Trans. on Nuc. Sci. **51**(1) (2004) 3-9.
- R. Schulte et. al, "Conceptual design of a proton computed tomography system for applications in proton radiation therapy." IEEE Trans. On Nuc. Sci. **51** (3) (2004) 866-872.
- L. Archambault et. Al, "Characterizing the response of miniature scintillation detectors when irradiated with proton beams." Phys. Med. Biol. **53** (2008) 1865-1876.
- R. Schulte et. al, "A maximum likelihood proton path formalism for application in proton computed tomography." Med. Phys. **35**(11) (2008) 4849-4856.

Scintillator measurements

- M. Hamada, “Range measurements using visible scintillation light for proton therapy.” Nuclear Science Symposium Conference Record, 2004. IEEE **3**(16-22) (2004). 1776-1777.
  - Recorded visible scintillation light generated by proton irradiation on a block of plastic scintillator
  - Analyzed the length, shapes, and brightness distribution to obtain the range, the magnitude of MCS, and the depth dose distribution
  - Range measured to within 0.7 mm
  - Critical data for GEANT4 code

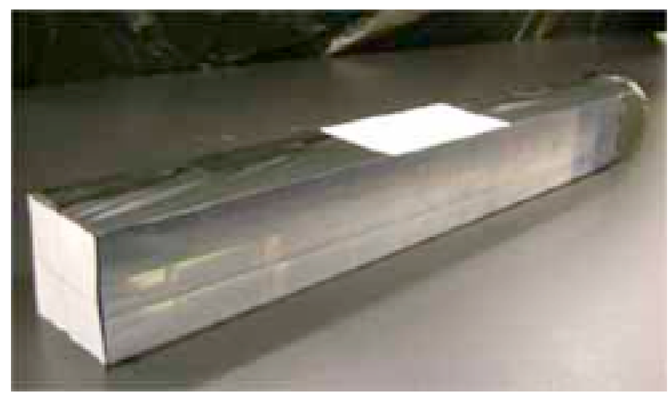

Fig. 1. Plastic scintillator block (*BICRON BC-400*, 50*50*400 mm)

Scintillator measurements

- L. Archambault et. Al, "Characterizing the response of miniature scintillation detectors when irradiated with proton beams." Phys. Med. Biol. **53** (2008) 1865-1876.
  - Points out that the main disadvantage of using scintillation detectors is scintillator quenching, which is an under-response of the irradiated scintillator as a function of incident LET
    - This means the number of scintillation photons produced per MeV deposited will vary as a function of the proton energy
    - Becomes more important as the beam energy decreases -> most important around Bragg peak
    - Need to take this into account in Monte Carlo simulation
  - Finds low amount of Cherenkov light (1% of total signal)
    - # of Cherenkov photons is low because the protons are not relativistic and the electrons they put into motion have low energies
  - Finds water equivalence
    - Dose deposited in plastic scintillator was always within 2% of the dose deposited in water except for 50 MeV protons at 3mm beyond Bragg peak

Still to determine

- Still unclear what energy of protons we need to have enter the detector in order to fully measure the Bragg peak and length extent
  - Carol said that at least 350 MeV is needed for proton radiography (400 MeV is good). Need to find out where she got this from.
- Need to further investigate detector designs